

Experimental Study of Sherwood-Nusselt Relation in Turbulent Convective Moist Airflow with Droplet Condensation as a Function of the Surface Properties

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DLR

Deutsches Zentrum
für Luft- und Raumfahrt
German Aerospace Center



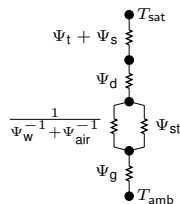
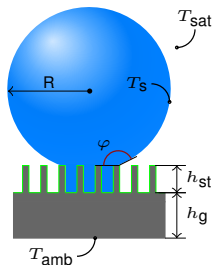
Motivation

Droplet condensation on surfaces: a phenomenon in technical applications and our everyday life



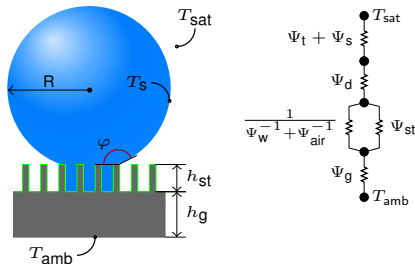
impact of surface properties on fogging and defogging of windshields

Heat transport on a rough surface with droplet condensation



thermal resistance : $\Psi_t = 2 T_s \sigma / R h_v \rho_v \dot{Q}$

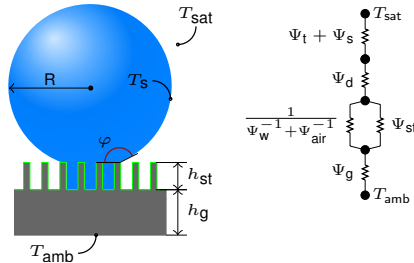
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droplet surface : $\Psi_s = 1 / \alpha_s 2 \pi R^2 (1 - \cos(\varphi))$

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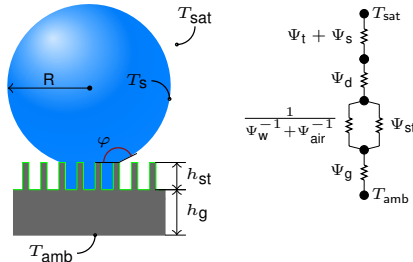


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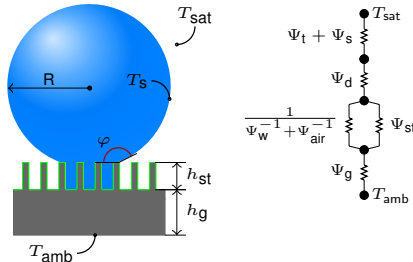
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surface structure : $(1 / \Psi_{st} + 1 / \Psi_w + 1 / \Psi_{air})^{-1} = h_{st} / \pi R^2 \lambda_{st} \sin^2(\varphi) (A_{air} \lambda_{air} + (1 - A_{air}) \lambda_w)$

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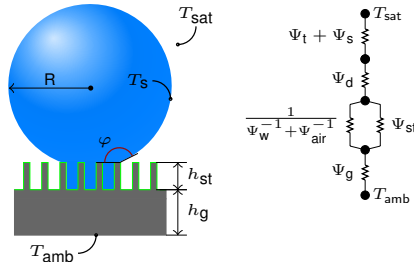
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glass pane : $\Psi_g = h_g / \pi R^2 \sin^2(\varphi) \lambda_g$

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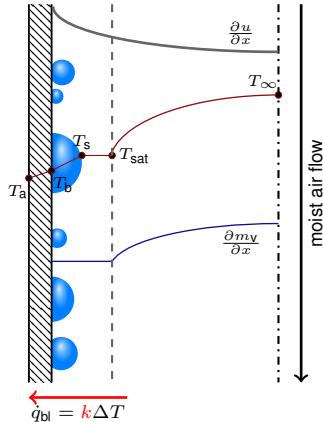
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total heat transmittance : $k = \left(\Psi_t + \Psi_s + \Psi_d + \left(\frac{1}{\Psi_{st}} + \frac{1}{\Psi_w} + \frac{1}{\Psi_{air}} \right)^{-1} + \Psi_g \right)^{-1}$

Heat and mass transfer in forced convection with phase transition

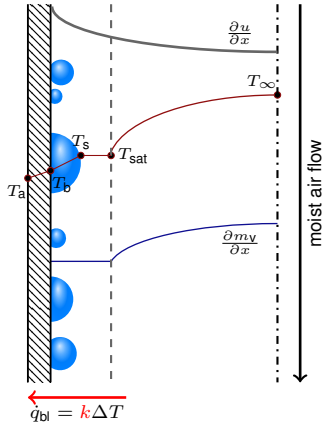
SYSTEM EQUATIONS



Heat and mass transfer in forced convection with phase transition

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$$\text{continuity : } \frac{D\rho}{Dt} = -\rho \nabla \cdot \vec{u}$$

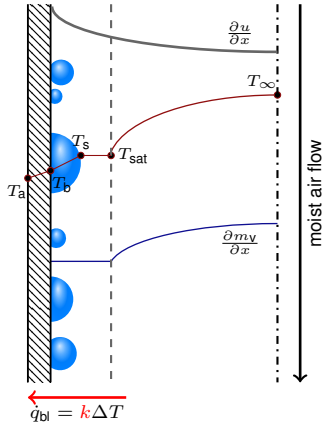


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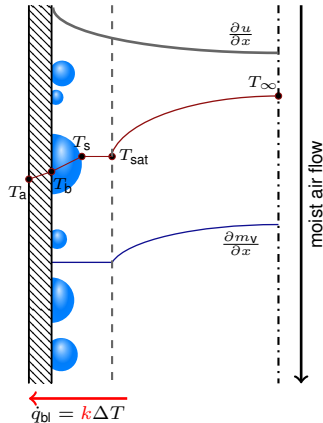
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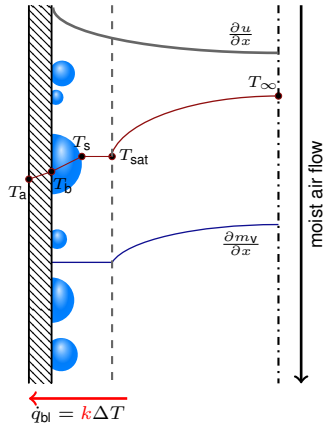
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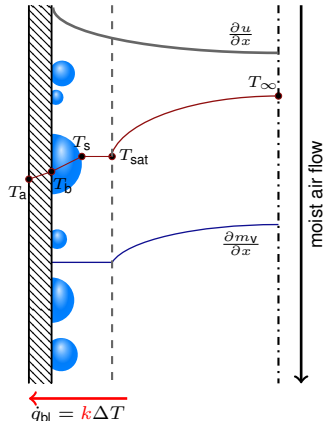
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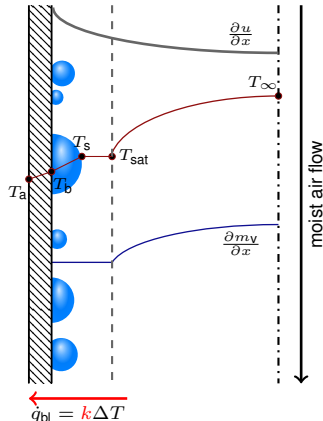
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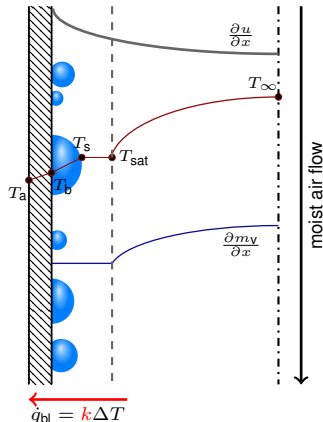
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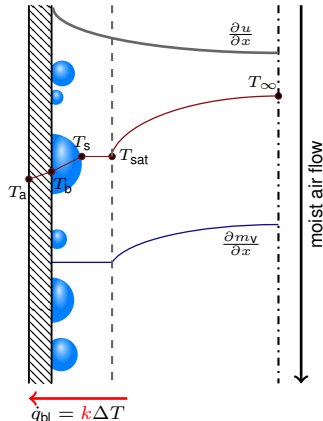
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SURFACE PROPERTIES



Heat and mass transfer in forced convection with phase transition

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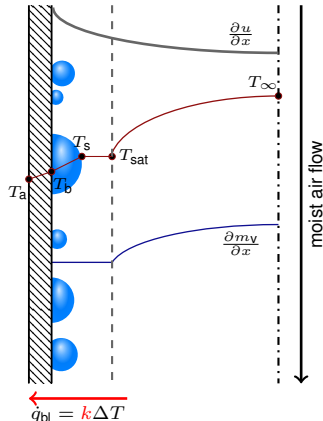
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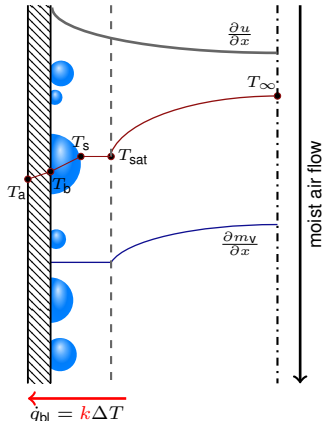
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$$\text{roughness : } R_z = \frac{\left| \sum_{i=1}^N Y_{p_i} \right| + \left| \sum_{i=1}^N Y_{v_i} \right|}{N}$$



Characteristic numbers

Cha. number	Definition	physical Interpretation
Reynolds	$Re = \frac{U_{in} d_h \varrho}{\eta}$	inertial forces to viscous forces
Contact angle	$\cos(\varphi) = \frac{\sigma_S - \sigma_{LS}}{\sigma_L}$	surface tensions
Roughness	$\epsilon = \frac{R_Z}{H} = \frac{1/N \sum_{i=1}^N Y_{p_i} + \sum_{i=1}^N Y_{v_i} }{L}$	ratio of R_Z^* to gap length
Prandtl	$Pr = \frac{\eta c_p}{\lambda_{air}}$	momentum to thermal diffusivity
Froude	$Fr = \frac{U_{in}}{\sqrt{\Delta \varrho / \varrho g L}}$	inertia to gravitational forces
Jakobs	$Ja = \frac{(T_{\infty} - T_w) c_p}{h_v}$	sensible to latent heat
Sherwood	$Sh = \frac{\dot{M}_v H}{A D_v \Delta \varrho_v}$	mass transfer to diffusion
Nusselt	$Nu = \frac{k L}{\lambda_{air}}$	convection to heat conductance

* DIN EN ISO 428

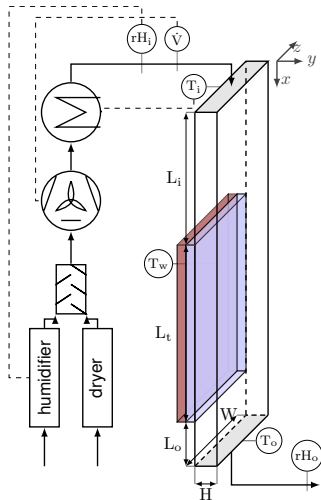
Gap wind tunnel / air supply system



Gap wind tunnel / air supply system

DIMENSIONS

height : $H = 20 \text{ mm}$ ○ width : $W = 529 \text{ mm}$

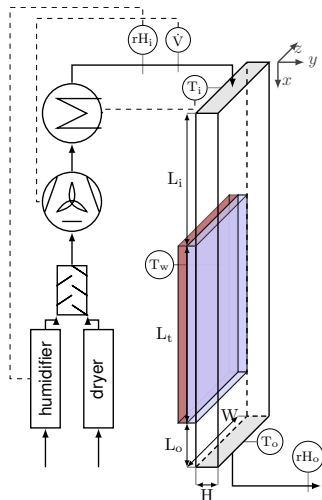


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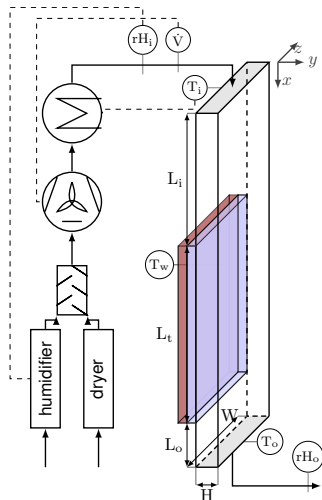
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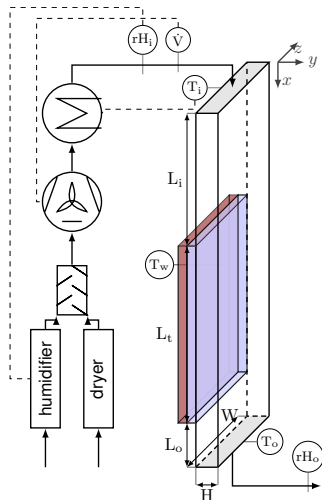
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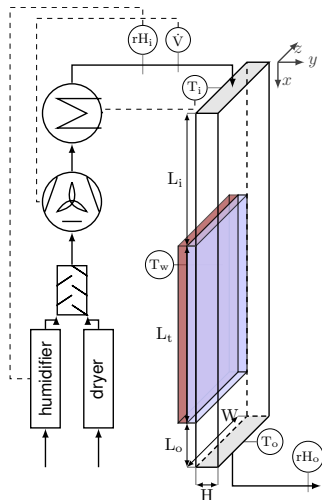
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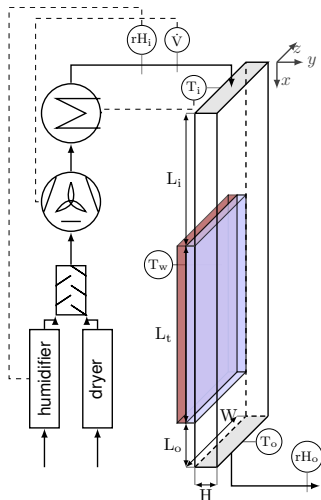
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BOUNDARY CONDITIONS

$$T_w = 12.5^\circ\text{C} + 7.5^\circ\text{C} \cdot \cos\left(2\pi \frac{t+900\text{s}}{\tau}\right), \tau = 3600 \text{ s}$$

$$T_{sw} = T_a$$

$\Theta_i [^\circ\text{C}]$	$T_i [^\circ\text{C}]$	$U [\text{m/s}]$	$Re [-]$
12.5	32.5	1.0	2200
12.5	32.5	2.0	4500
13.5	32.5	2.9	6600



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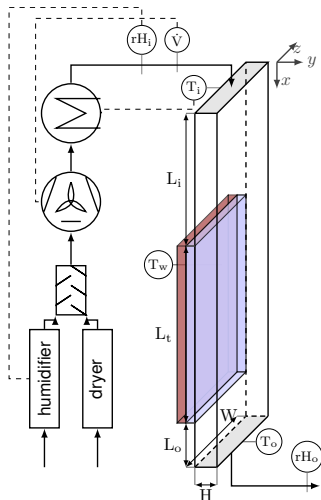
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SURFACE PROPERTIES GLASS PANE



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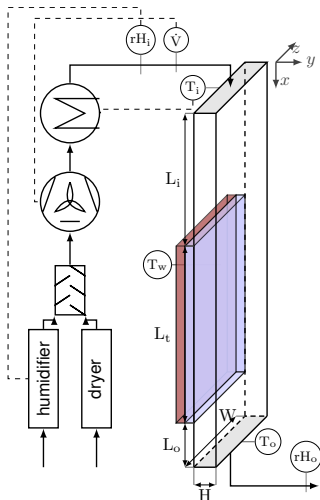
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surface	$R_z [\text{nm}]$	$\epsilon = R_z/H [-]$	contact angle $\varphi [^\circ]$
hydrophobic	≈ 60	0.3×10^{-5}	 101 ± 2
hydrophilic	≈ 60	0.3×10^{-5}	 33 ± 5
polyester I	230	1.15×10^{-5}	 72 ± 2
polyester II	650	3.25×10^{-5}	 67 ± 3



Heat balance

$$\dot{Q}_t =$$

$$\dot{Q}_g +$$

$$\dot{Q}_{sw} +$$

$$\dot{Q}_{pt}$$

Heat balance

$$\dot{Q}_t = \dot{Q}_g + \dot{Q}_{sw} + \dot{Q}_{pt}$$

$$c_p^{\text{air}} \dot{M}_{\text{air}} (T_i - T_o) = W L k (T_m - T_w) + L (2 H + W) k_{sw} (T_m - T_a) + \dot{M}_v H_v$$

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$$T(x) = \frac{W k T_w + (2 H + W) k_{sw} + \exp \left(\left(-\frac{x}{c_p^{\text{air}} \dot{M}_{\text{air}}} + C \right) (W k + (2 H + W) k_{sw}) \right)}{(W k + (2 H + W) k_{sw})}$$

$$C = -\frac{\ln (W k T_w + T_i (W k + (2 H + W) k_{sw})) - (2 H + W) k_{sw}}{(W k + (2 H + W) k_{sw})}$$

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$$\dot{Q}_t = \dot{Q}_g + \dot{Q}_{sw} + \dot{Q}_{pt}$$

$$c_p^{\text{air}} \dot{M}_{\text{air}} (T_i - T_o) = W L k (T_m - T_w) + L (2 H + W) k_{sw} (T_m - T_a) + \dot{M}_v H_v$$

$$c_p^{\text{air}} \dot{M}_{\text{air}} dT = [W k (T(x) - T_w) + (2 H + W) k_{sw} (T(x) - T_a)] dx + \dot{M}_v(x) H_v$$

$$T(x) = \frac{W k T_w + (2 H + W) k_{sw} + \exp \left(\left(-\frac{x}{c_p^{\text{air}} \dot{M}_{\text{air}}} + C \right) (W k + (2 H + W) k_{sw}) \right)}{(W k + (2 H + W) k_{sw})}$$

$$C = -\frac{\ln (W k T_w + T_i (W k + (2 H + W) k_{sw})) - (2 H + W) k_{sw}}{(W k + (2 H + W) k_{sw})}$$

calculating k for $T(L) = T_o$

System temperatures

$$Re = 2200$$

$$\epsilon = 1.15 \times 10^{-5}$$

$$\varphi = 72$$

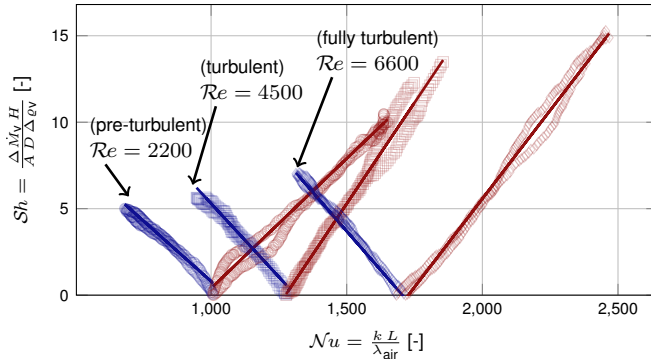
$$T_i = 32^\circ\text{C}$$

$$\Theta_i = 12.5^\circ\text{C}$$

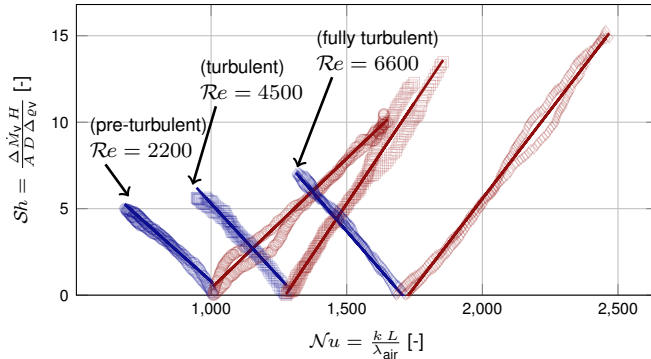
$$\text{total time} = 7200\text{s}$$

- phase change
- no phase change

Sh - Nu dependency as a function of Re



Sh - Nu dependency as a function of Re



- linear relation $Sh = m Nu + C$

$$Re = 2200$$

$$|m_c| = 0.014, |m_e| = 0.015$$

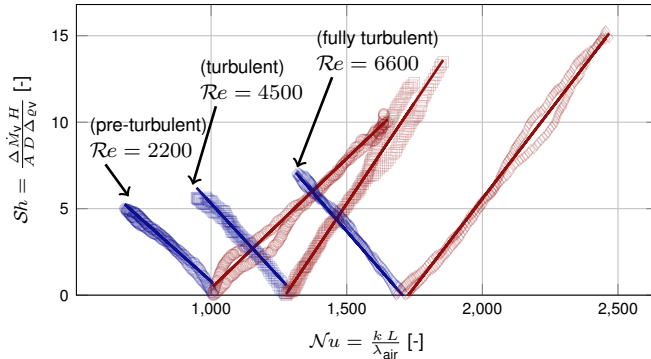
$$Re = 4500$$

$$|m_c| = 0.017, |m_e| = 0.022$$

$$Re = 6600$$

$$|m_c| = 0.018, |m_e| = 0.021$$

Sh - Nu dependency as a function of Re



● condensation

● evaporation

$$\epsilon = 1.15 \times 10^{-5}$$

$$\varphi = 72^\circ$$

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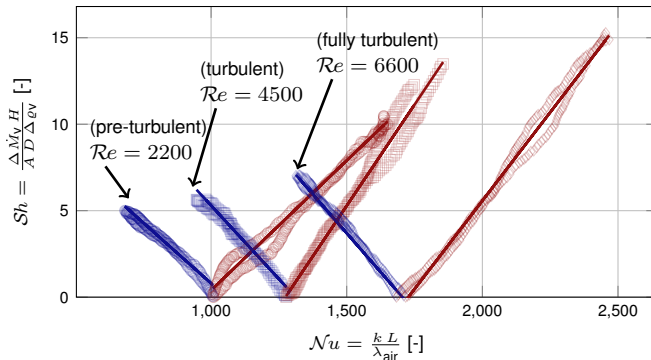
$$|m_c| = 0.017, |m_e| = 0.022$$

$$Re = 6600$$

$$|m_c| = 0.018, |m_e| = 0.021$$

- linear relation $Sh = m Nu + C$
- $Re = 2200$ similar slopes $|m|$ for condensation and evaporation

Sh - Nu dependency as a function of Re



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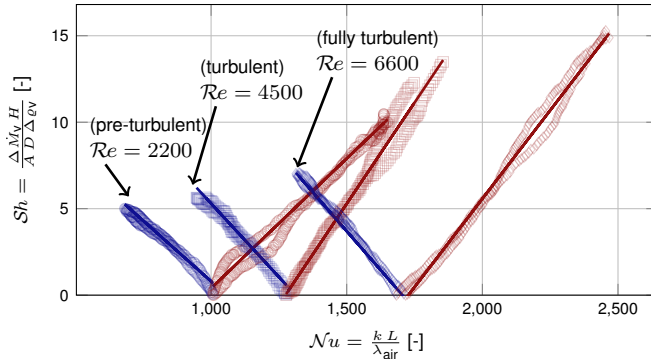
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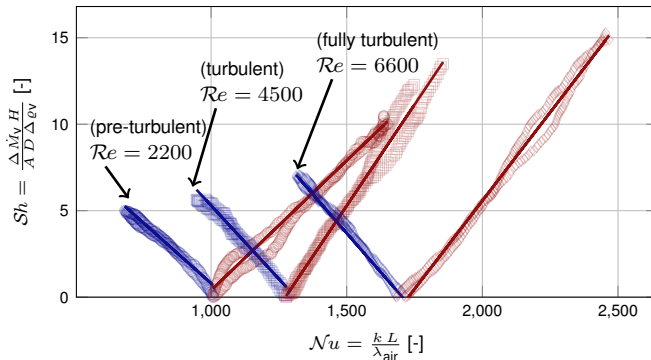
- linear relation $Sh = m Nu + C$
- $Re = 2200$ similar slopes $|m|$ for condensation and evaporation
- $Re = 4500$ and $Re = 6600$ (turbulent) different slopes $|m|$ for condensation and evaporation

Sh - Nu dependency as a function of Re



- linear relation $Sh = m Nu + C$
- $Re = 2200$ similar slopes $|m|$ for condensation and evaporation
- $Re = 4500$ and $Re = 6600$ (turbulent) different slopes $|m|$ for condensation and evaporation
- higher slopes $|m|$ for condensation and evaporation in case of turbulent flow

Sh - Nu dependency as a function of Re



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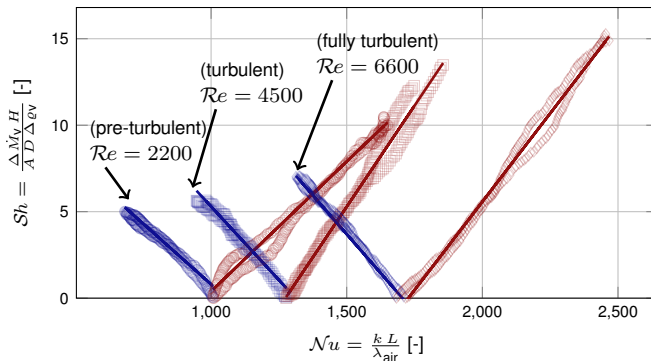
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- higher $|m|$ for turbulent indicates higher mass transfer due to phase transition in ratio to diffusive mass transfer

Sh - Nu dependency as a function of Re



● condensation

● evaporation

$$\epsilon = 1.15 \times 10^{-5}$$

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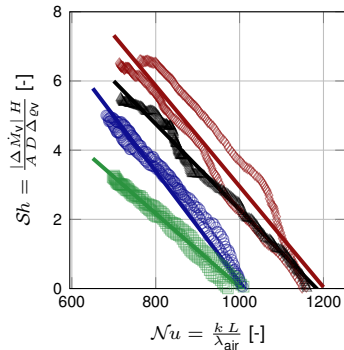
$$Re = 6600$$

$$|m_c| = 0.018, |m_e| = 0.021$$

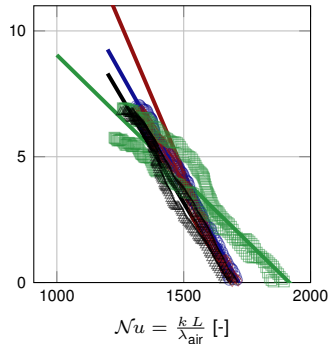
- linear relation $Sh = m Nu + C$
- $Re = 2200$ similar slopes $|m|$ for condensation and evaporation
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- higher $|m|$ for turbulent indicates higher mass transfer due to phase transition in ratio to diffusive mass transfer
- onset of condensation at higher Nu for higher Re due to higher mean fluid temperatures

Sh - Nu -relation in case of condensation

$Re = 2200/2300$



$Re = 6600$



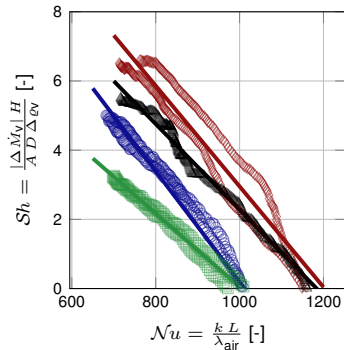
- $\epsilon = 1.15 \cdot 10^{-5}$, $\varphi = 72^\circ$
- $\epsilon = 3.25 \cdot 10^{-5}$, $\varphi = 68^\circ$
- $\epsilon \approx 0.3 \cdot 10^{-5}$, $\varphi = 101^\circ$
- $\epsilon \approx 0.3 \cdot 10^{-5}$, $\varphi = 33^\circ$

- $|m| = 0.014$ • $|m| = 0.015$
- $|m| = 0.010$ • $|m| = 0.011$

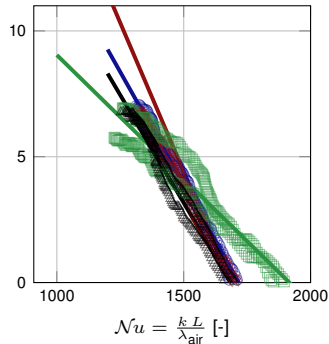
- $|m| = 0.018$ • $|m| = 0.023$
- $|m| = 0.010$ • $|m| = 0.017$

Sh - Nu -relation in case of condensation

$Re = 2200/2300$



$Re = 6600$



- $\epsilon = 1.15 \cdot 10^{-5}$, $\varphi = 72^\circ$
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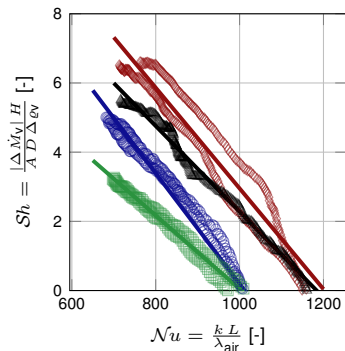
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- $|m| = 0.010$ • $|m| = 0.011$

- $|m| = 0.018$ • $|m| = 0.023$
- $|m| = 0.010$ • $|m| = 0.017$

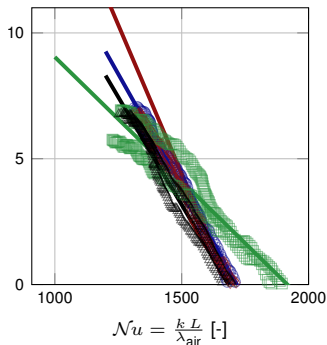
- for hydrophobic surface the slope $|m|$ seems to be independent of Re

Sh - Nu -relation in case of condensation

$Re = 2200/2300$



$Re = 6600$



- $\epsilon = 1.15 \cdot 10^{-5}$, $\varphi = 72^\circ$
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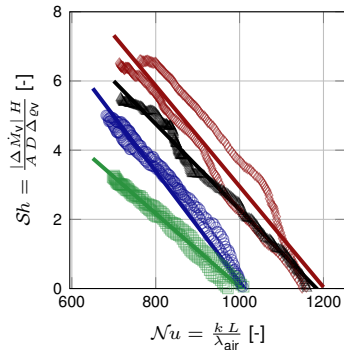
- $|m| = 0.014$ • $|m| = 0.015$
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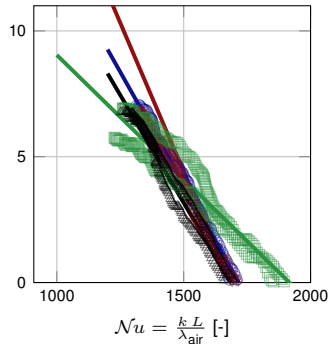
- for hydrophobic surface the slope $|m|$ seems to be independent of Re
- for the other surfaces $|m|$ increases for higher Re

Sh - Nu -relation in case of condensation

$Re = 2200/2300$



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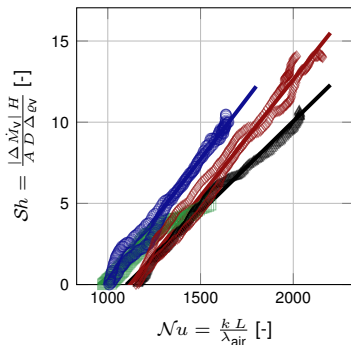
- $|m| = 0.014$ • $|m| = 0.015$
- $|m| = 0.010$ • $|m| = 0.011$

- $|m| = 0.018$ • $|m| = 0.023$
- $|m| = 0.010$ • $|m| = 0.017$

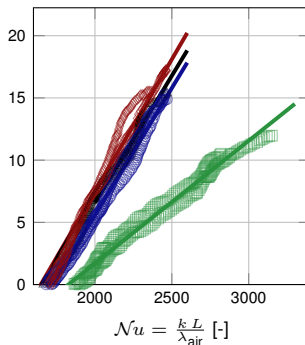
- for hydrophobic surface the slope $|m|$ seems to be independent of Re
- for the other surfaces $|m|$ increases for higher Re
- slope $|m|$ increases in case of higher surface roughness ϵ

Sh - Nu -relation in case of evaporation

$Re = 2200/2300$



$Re = 6600$

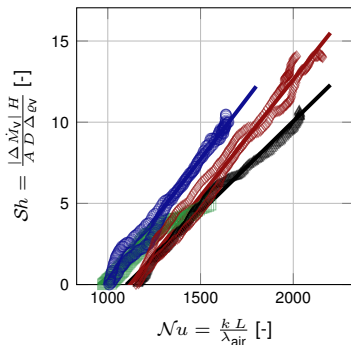
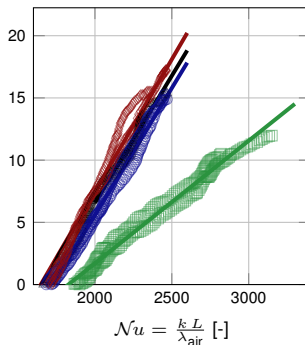


- $\epsilon = 1.15 \cdot 10^{-5}$, $\varphi = 72^\circ$
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- $|m| = 0.015$
- $|m| = 0.015$
- $|m| = 0.010$
- $|m| = 0.010$

- $|m| = 0.022$
- $|m| = 0.021$
- $|m| = 0.010$
- $|m| = 0.020$

Sh - Nu -relation in case of evaporation

 $Re = 2200/2300$

 $Re = 6600$


● $\epsilon = 1.15 \cdot 10^{-5}$, $\varphi = 72^\circ$

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● $|m| = 0.015$ ● $|m| = 0.015$

● $|m| = 0.010$ ● $|m| = 0.010$

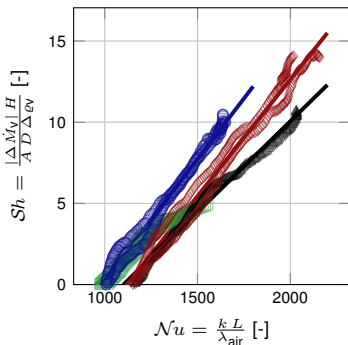
● $|m| = 0.022$ ● $|m| = 0.021$

● $|m| = 0.010$ ● $|m| = 0.020$

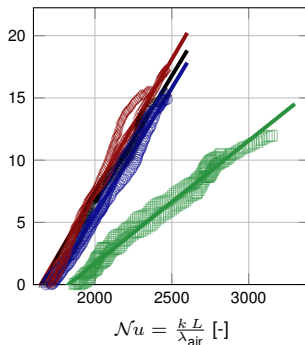
○ higher slopes $|m|$ for turbulent flow except hydrophobic surface

Sh-Nu-relation in case of evaporation

$Re = 2200/2300$



$Re = 6600$



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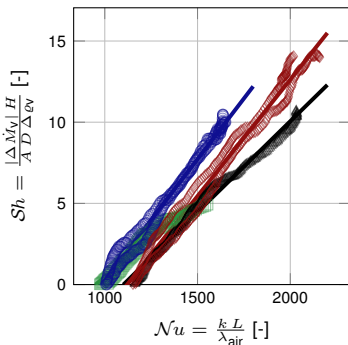
- $|m| = 0.015$ ● $|m| = 0.015$
- $|m| = 0.010$ ● $|m| = 0.010$

- $|m| = 0.022$ ● $|m| = 0.021$
- $|m| = 0.010$ ● $|m| = 0.020$

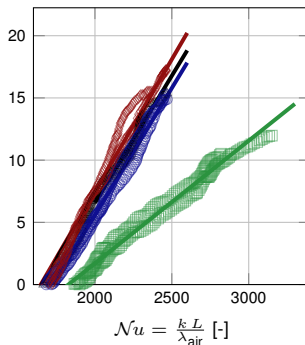
- higher slopes $|m|$ for turbulent flow except hydrophobic surface
- rougher surfaces have the same slope $|m|$ as well as smoother surfaces have the same slope $|m|$

Sh - Nu -relation in case of evaporation

$Re = 2200/2300$



$Re = 6600$



- $\epsilon = 1.15 \cdot 10^{-5}$, $\varphi = 72^\circ$
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- $\epsilon \approx 0.3 \cdot 10^{-5}$, $\varphi = 33^\circ$

- $|m| = 0.015$ ● $|m| = 0.015$ ● $|m| = 0.022$ ● $|m| = 0.021$
- $|m| = 0.010$ ● $|m| = 0.010$ ● $|m| = 0.010$ ● $|m| = 0.020$

- higher slopes $|m|$ for turbulent flow except hydrophobic surface
- rougher surfaces have the same slope $|m|$ as well as smoother surfaces have the same slope $|m|$
- in case of $Re = 6600$ slopes are almost similar for all surfaces except hydrophobic surface

Summary

- definition and characterisation of mass and heat transport in forced convective air flow with phase transition

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- different slopes for condensation and evaporation for all surfaces except of hydrophobic
- increased slopes in case of higher Re indicating vapour mass transfer due to small scale turbulent flow structures becoming more dominant relating to the diffusive mass transfer

THANK YOU FOR YOUR ATTENTION!



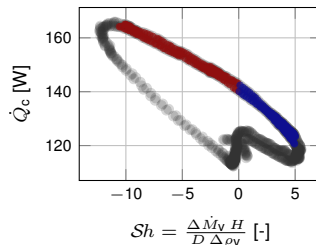
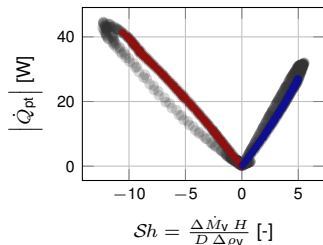
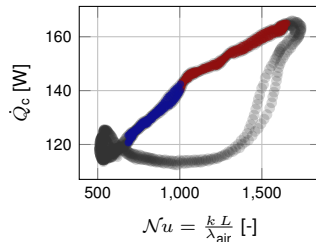
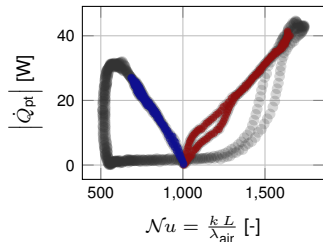
Deutsches Zentrum
für Luft- und Raumfahrt
German Aerospace Center

ACKNOWLEDGEMENT

This investigation has been funded by the German Association of the Automotive Industry (VDA) in the research project experimental study of condensation on glass panes as a function of surface properties

<https://www.vda.de/de/services/Publikationen/fat-schriftenreihe-307.html>

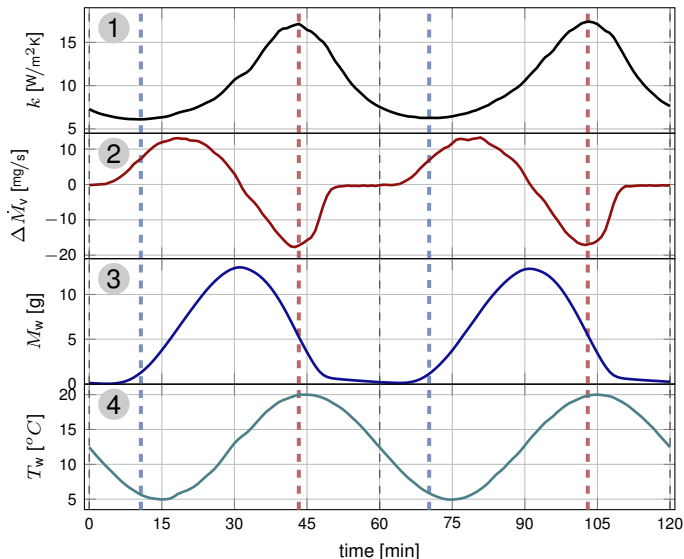
Heat transmittance and phase transition



$Re = 2200$
 $\epsilon = 3.25 \times 10^{-5}$
 $\varphi = 72$
 $T_{in} = 32^\circ\text{C}$
 $\Theta_i = 12.5^\circ\text{C}$
 total time = 7200s

● condensation
 ● evaporation

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